REMARKS

Claims 1-50 and 55-58 were pending in the application. In response to the Examiner's Election Requirement of April 28, 2006, Applicant elected Claims 1-8, 10, 11, 13-26, 30-46, 50, and 55-57. Accordingly, Applicant withdraws Claims 9, 12, 27-29, 47-49, and 58 from examination without prejudice or disclaimer. Claim 34 is canceled without prejudice or disclaimer. New Claims 59-66 are added. After entry of this amendment, Claims 1-8, 10, 11, 13-26, 30-33, 35-46, 50, 55-57, and 59-66 will be pending for examination.

In the Office Action dated September 25, 2006 the Examiner rejected Claims 1-8, 10, 11, 13-26, 30-33, 35-46, 50, and 55-57. Applicant respectfully requests the rejection of these Claims be reconsidered in light of the foregoing amendments and the following remarks.

The rejections will be discussed in the order raised by the Examiner.

35 U.S.C. § 112 REJECTIONS

The Examiner rejected Claims 2-6, 16, 19-21, 30, 35, 38, and 39 as being indefinite. Claims 2 and 19 are amended to clarify the antecedent basis in Claims 2-6 and 19-21 for recitations of "said mode locking mechanism." Claim 16 is amended to recite that the laser outputs "light." Claim 30 is amended to clarify the antecedent basis for "said ultra-short optical pulses." Claim 35 is amended to correct a typographical error and to clarify the antecedent basis for "said optical fiber." Claims 38 and 39 are amended to clarify functioning of the mode filter. Support for these amendments is at least found in the original Claims as filed. These amendments do not narrow the scope of any of the Claims.

Applicant respectfully requests the Examiner to withdraw the Section 112 rejections of Claims 2-6, 16, 19-21, 30, 35, 38, and 39.

35 U.S.C. § 102 REJECTIONS

A. Fermann I

Claims 1-4, 7, 16-19, 22-26, 30-41, 50, and 55-57 are rejected as anticipated by US Patent No. 5,627,848 (Fermann I). Applicant respectfully traverses these rejections.

Claim 1 recites a laser comprising, among other limitations, "a length of multi-mode optical fiber having a cladding and doped with a gain medium and positioned along said cavity

axis." The Examiner asserts that "multi-mode optical fibers" include "fibers that guide multi-modes, whether through the core *or within the cladding*" (emphasis added). Applicant respectfully disagrees with the Examiner's assertion that a multi-mode fiber includes a fiber with cladding-guided multi-modes. As will be discussed further below, at least because Fermann I does not teach a *multi-mode optical fiber* having a cladding and doped with a gain medium, Applicant respectfully submits that the Examiner's rejections are improper.

Single- and Multi-Mode Optical Fibers

Applicant notes that pursuant to M.P.E.P. § 2111.01, the terms of a claim are to be given their "plain meaning," which is "the meaning that the term would have to a person of ordinary skill in the art in question at the time of the invention, *i.e.*, as of the effective filing date of the patent application." See *Phillips v. AWH Corp.*, 415 F.3d 1303, 1313 (Fed. Cir. 2005) (*en banc*).

Applicant respectfully submits that when read in the context of the specification and claims a person of ordinary skill would understand a multi-mode optical fiber to refer to an optical fiber comprising a *core* that can support propagation of modes in addition to the fundamental mode. The specification teaches that "a fiber is considered multi-mode when the V-value exceeds 2.41." See, paragraph [0047]. As is well known in the art, the V-value (or normalized frequency) depends on the size of the fiber *core* (e.g., its radius *a*) relative to the wavelength of light λ propagating in the core.

The Federal Standard FS-1037C (Telecommunications: Glossary of Telecommunication Terms), which the Examiner cites on pages 11-12 to show definitions of terms in the technological arts, provides the following definition of "normalized frequency (V)" (emphasis added):

> **normalized frequency (*V*): 1.** In an optical fiber, a dimensionless quantity, V, given by
>
> $$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} ,$$
>
> where a is the core radius, λ is the wavelength in vacuum, n_1 is the maximum refractive index of the core, and n_2 is the refractive index of the homogeneous cladding. *Note 1:* In multimode operation of an optical fiber having a power-law refractive index profile, the approximate number of bound modes, *i.e.,* the mode volume, is given by

$$\frac{V^2}{2}\left(\frac{g}{g+2}\right),$$

> where V is the normalized frequency greater than 5 and g is the profile parameter. *Note 2:* For a step index fiber, the mode volume is given by $V^2/2$. For single-mode operation, $V < 2.405$. Synonym V number.

Applicant respectfully points out that the teaching of the specification that multi-mode operation occurs for a V-value *greater* than 2.41 is consistent with the above definition of single-mode operation for V *less* than 2.405 (see, Note 2 above). Therefore, the FS-1037C standard shows that single-mode and multi-mode fibers are distinguished by light propagation properties of the fiber *core* and not light propagation within the fiber *cladding* as asserted by the Examiner.

The FS-1037C standard provides further support that fiber *core modes*, and not cladding modes, are used to distinguish single- and multi-mode fibers. As indicated in Notes 1 and 2 of the above definition, the V-number is related to the number of "bound modes" in the fiber, which the FS-1037C standard defines as follows:

> **bound mode:** In an optical fiber, a mode that (a) has a field intensity that decays monotonically in the transverse direction everywhere external to the <u>core</u> and (b) does not lose power to radiation. *Note:* Except for single-mode fibers, the power in bound modes is predominantly contained in the <u>core</u> of the fiber. *Synonyms* guided mode, trapped mode. (emphasis added)

Accordingly, bound modes represent propagating modes in the fiber *core,* and the number of such modes may be used to distinguish single-mode and multi-mode fibers. The number of propagating core modes can be determined from the V-number. Applicant respectfully submits that the FS-1037C standards clearly show that a person of ordinary skill would understand that a "multi-mode fiber" is characterized by the number of propagating *core* modes and *not* by the number of cladding modes (which the FS-1037C standard states are "undesired").

The Examiner cites U.S. Patent No. 4,829,529 (Kafka) to support his assertion regarding the scope of the recitation of "multi-mode fiber." Applicant respectfully disagrees with the Examiner's characterization of Kafka. The fiber disclosed in Kafka (see, e.g., Figs. 1,2, and 4) is known in the art as a doubly-clad (or double-clad) fiber defined by the FS-1037C standard as a "single-mode fiber that has two claddings."

Additionally, as discussed by Applicant's representatives during the interview, the Exhibits presented (copies attached) establish that well-known fiber optic reference sources characterize single- and multi-mode fibers by the properties of propagating *core* modes, not cladding modes. Moreover, the Exhibits further establish that single- and multi-mode fibers can be defined by the V-value of the *core* of the fiber. See, e.g., Exhibit 1, p. 10.10; Exhibit 2, p. 317; and Exhibit 4, p. 116-118.

In summary, Applicant respectfully submits that the plain meaning of the term "multi-mode optical fiber," as used in the specification and claims, is a fiber comprising a core capable of propagating optical modes in addition to the fundamental mode. A fiber is considered multi-mode if $V > 2.405$, with V determined by core properties (e.g., core radius).

Fermann I discloses a double-clad optical fiber comprising a single-mode core. The core properties described in column 4, l. 20-40 result in a V-value of about 2, which is well-below the upper limit (2.405) of the single-mode regime. Accordingly, Fermann I discloses a single-mode fiber and does not teach or suggest multi-mode fibers as used in the specification and claims.

Independent Claim 1

Claim 1 recites a laser comprising, among other limitations, "a length of *multi-mode optical fiber*" and "an optical guide positioned on said cavity axis which confines the light amplified by said *multi-mode optical fiber* to preferentially the fundamental mode of said *multi-mode optical fiber*." As discussed above, Fermann I does not disclose a multi-mode optical fiber in a laser.

Applicant respectfully requests the Examiner to withdraw the rejection of Claim 1 as anticipated by Fermann I.

Independent Claim 55

Claim 55 recites a method comprising, among other limitations, amplifying "light energy within said laser cavity in a bent *multi-mode fiber*" and "confining said light energy within said laser cavity substantially to the fundamental mode of said *multi-mode fiber*." As discussed above, Fermann I does not disclose methods using multi-mode optical fiber.

For at least this reason, Applicant respectfully requests the Examiner to withdraw the rejection of Claim 55 as anticipated by Fermann I.

Dependent Claims

Claims 2-4, 7, 16-19, 22-26, 30-33, 35-41, 50 depend from Claim 1 and Claims 56-57 depend from Claim 55. The dependent claims include all the limitations of the base independent claims, respectively, as well as additional limitations that define the scope of the inventions in these dependent claims. Because Fermann I does not disclose all the limitations of independent Claims 1 and 55, Applicant respectfully submits that the rejection of the claims depending from the independent claims is improper. For at least this reason, Applicant respectfully requests withdrawal of the rejection of Claims 2-4, 7, 16-19, 22-26, 30-33, 35-41, 50, 56-57 as anticipated by Fermann I.

B. Wyatt

Claims 1, 7, 8, 17, 18, 35-39, 46, and 50 are rejected as anticipated by US Patent No. 5,422,897 (Wyatt). Applicant respectfully traverses these rejections.

Claim 1 recites, among other limitations, "a pump coupled to said cladding" of a multi-mode optical fiber. Wyatt does not disclose pump light coupled to the cladding. In Wyatt, the pump light is coupled to the multi-mode *core* of a single-clad fiber. See, e.g., col. 1, l. 56-62; and col. 4, l. 52-64. For example, Wyatt teaches that the numerical aperture (NA) of the multimode fiber core should large, e.g., by having "as high a value of Δn [refractive index difference between core and cladding] as possible to enable optimum coupling of light from the pump source into the multimode fiber." See, col. 1, l. 59-62 and col. 5, l. 23-25. It is well known in the art that a large NA permits greater coupling of optical energy into the *core* of a single-clad fiber.

Wyatt also describes the use of a computer generated hologram (CGH) as an optical coupling means for coupling the pump power into the multimode fiber. See, col. 6, l. 2-5. The CGH is used to convert the output of the pump (e.g., a laser diode array) "to a focused spot." See, col. 1, l. 53-55. Such a focused spot provides good optical coupling to the core of the fiber.

Moreover, Wyatt teaches away from coupling pump light to the cladding. For example, Wyatt describes an example of a cladding-pumped double-clad fiber in which pump light is launched into an elliptical outer core of the fiber. See, col. 2, l. 3-10. Wyatt describes the arrangement as having "an extremely complex structure, which makes fabrication very difficult." See, col. 2, l. 6-7. Performance is "highly dependent on launch conditions" which are described

as being "complicated." See, col. 2, l. 8-10. To avoid these difficulties, Wyatt pumps light into the high-NA *core* of a multi-mode fiber. See, col. 1, l. 59-62 and col. 5, l. 23-25.

Accordingly, Applicant respectfully submits that Wyatt discloses pump light coupled to a multi-mode fiber *core* and does not teach or suggest "a pump coupled to said cladding" as recited in Claim 1. For at least this reason, Wyatt does not teach or suggest all the limitations of Claim 1; therefore, the anticipation rejection of Claim 1 is improper.

Also, for at least this reason, the rejections of Claims 7, 8, 17, 18, 35-39, 46, and 50, which depend from Claim 1 and include further limitations, are improper. Applicant respectfully requests withdrawal of the anticipation rejections based on Wyatt.

C. Fermann II

Claims 1, 7, 13, 14, 16-18, 22, 23, 25, 30-32, 35-38, 46, and 50 are rejected under 35 U.S.C. §§ 102(a) and 102(e) as being anticipated by U.S. Patent No. 5,818,630 (Fermann II). Applicant respectfully traverses these rejections.

The inventors of the Fermann II patent are Martin E. Fermann and Donald J. Harter. The inventor of the claims of the present application is Martin E. Fermann. Attached to this amendment is a declaration by Martin E. Fermann and Donald J. Harter, pursuant to 37 C.F.R. § 1.132, that establishes, to the extent the inventions of Claims 1, 7, 13, 14, 16-18, 22, 23, 25, 30-32, 35-38, 46, and 50 are disclosed in U.S. Patent No. 5,818,630, the inventions in these claims were not patented "before the invention thereof by the applicant for patent" as required by 35 U.S.C. § 102(a) and were not "by another" as required under 35 U.S.C. § 102(e). See, also, M.P.E.P. 706.02(b).

Accordingly, based on the attached declaration, Applicant overcomes the Examiner's rejection of these claims and requests withdrawal of the rejection based on Fermann II.

35 U.S.C. § 103 REJECTIONS

Applicant notes that to establish a prima facie case of obviousness, three basic criteria must be met:

> First, there must be some suggestion or motivation, either in the references themselves or in the knowledge generally available to one of ordinary skill in the art, to modify the reference or to combine reference teachings. Second, there must be a reasonable expectation of success. Finally, the prior art reference (or

references when combined) must teach or suggest all the claim limitations. M.P.E.P. 2143.

Applicant respectfully submits that the cited references, either alone or in any combination, do not, at least, teach or suggest all the limitations of rejected Claims 2-6, 8-11, 13-16, 19-26, 30-33, 40-45, and 55-57. Applicant also respectfully submits that the Examiner has not identified a suggestion or motivation for combining the references or that there is a reasonable expectation of success. For at least theses reasons, Applicant traverses the Examiner's Section 103 rejections.

A. Fermann I

Claims 5, 6, 8-11, 13-15, 20, 21, and 42-45 are rejected as being unpatentable over Fermann I either alone or in various combinations with other cited art. These claims depend from and include all the limitations of Claim 1, which recites, among other limitations, "a length of multi-mode optical fiber" and "an optical guide positioned on said cavity axis which confines the light amplified by said multi-mode optical fiber to preferentially the fundamental mode of said multi-mode optical fiber."

As discussed further above, Applicant respectfully submits that Fermann I discloses only a single-mode fiber and does not teach or suggest at least the limitations of Claim 1 (and its dependent claims) reciting multi-mode fiber. In the Section 103 rejections, the Examiner relies on Fermann I or the other cited references for teaching or suggesting additional limitations of the claims, but *not* as teaching or suggesting use of multi-mode fiber as recited in the claims. Accordingly, Applicant respectfully submits the Examiner's obviousness rejections are improper at least because the various combinations of cited references do not teach or suggest all the claim limitations. The claim rejections will be discussed further below.

<u>Claims 5, 6, 20, and 21</u>

These claims stand rejected over Fermann I alone. Since, as previously discussed, Fermann I does not teach or suggest multi-mode fiber as recited in these claims, Applicant respectfully requests these rejections be withdrawn.

<u>Claims 8-11, 13-15, and 42-45</u>

Applicant respectfully submits the Examiner has not established a *prima facie* obviousness rejection of Claims 8-11, 13-15, and 42-45 at least because the Examiner has not

identified any teaching or suggestion in any of the cited references (alone or in combination) for multi-mode optical fiber as recited in these claims. Accordingly, Fermann I and the other references (alone or in combination) do not teach or suggest all the claim limitations, and Applicant respectfully requests withdrawal of the rejections of these claims.

Additionally, Applicant respectfully disagrees with the Examiner's contentions that the cited references teach or suggest various other claim limitations. For example, the Examiner cites U.S. Patent No. 5,074,633 (Cohen) for teaching fusion splice tapered connection of fibers. Applicant notes that Cohen describes a fusion splice between two single-clad fibers, which are "typically single-mode fibers." Col. 4, l. 20-21. Cohen does not teach or suggest, for example, fiber connections where "said single-mode mode-filter fiber is fusion spliced onto one end of said multi-mode optical fiber" as recited in Claims 8-11. Also, the Examiner cites the Goldberg reference for teaching v-groove side pumping. However, Goldberg teaches forming a v-groove on a fiber having a single-mode core (see, p. 208) and not "a v-groove on said multi-mode optical fiber for coupling said pump to said multi-mode fiber."

B. Wyatt

Claims 2-6, 9-11, 13-16, 19-26, 30-33, 40-45, and 55-57 are rejected as being unpatentable over Wyatt in combination with other cited references. Applicant respectfully traverses these rejections.

<u>Claims 2-6, 9-11, 13-16, 19-26, 30-33, and 40-45</u>

These claims depend from and include all the limitations of Claim 1 as well as other limitations which further define the scope of the inventions in these claims. Claim 1 recites, among other limitations, "a pump coupled to said cladding" of a multi-mode optical fiber. As discussed above, Applicant respectfully submits that Wyatt discloses coupling pump light to a multi-mode fiber *core* and does not teach or suggest "a pump coupled to said cladding" as recited in Claim 1.

Applicant respectfully submits the Examiner has not established a *prima facie* obviousness rejection of Claims 2-6, 9-11, 13-16, 19-26, 30-33, and 40-45 at least because the Examiner has not identified any teaching or suggestion in any of the cited references (alone or in combination) for a pump coupled to the cladding of a multi-mode optical fiber as recited in these claims. Accordingly, Wyatt and the other references (alone or in combination) do not teach or

suggest all the claim limitations, and Applicant respectfully requests withdrawal of the rejections of these claims.

Additionally, Applicant respectfully disagrees with the appropriateness of the Examiner's combination of the cited references. As noted above, there must be a suggestion or motivation to combine the references as well as a reasonable expectation of success.

For example, regarding Claims 2-6, 19-21, and 30, the Examiner cites the combination of Wyatt, Fermann I, and an article to DeSouza. Applicant agrees with the Examiner that Wyatt does not teach or suggest modelocking. However, Applicant respectfully submits that the Examiner has not established a suggestion or motivation to combine the references, or that, even if combined, there would be a reasonable expectation of success. For example, to the extent that Fermann I and DeSouza disclose modelocking, it is in the context of *single-mode* fibers and not *multi-mode* fibers as recited in this application's claims. The present application teaches that the stability of modelocked depends critically on minimizing spurious reflections in the oscillator, which are conceptually equivalent to mode-coupling in multi-mode fibers. See, paragraphs [0030]-[0031]. The application also teaches that mode-coupling of higher order modes in a multi-mode fiber also suppresses mode-locking. Id.; see, also, Fermann I, col. 5, l. 38-60. In fact, as of the filing date of the application, modelocking of a multi-mode fiber was considered "impossible." See, paragraph [0031].

Accordingly, Applicant respectfully submits that the Examiner has not identified why a person of ordinary skill would be motivated to combine any possible teachings of Fermann I and DeSouza regarding modelocking in a single-mode fiber to the more difficult problem of modelocking in a multi-mode fiber. Additionally and for the sake of argument only, even if the references are combined, the Examiner has not demonstrated that any combined teachings relevant to modelocking in single-mode fibers will provide a reasonable expectation of success for modelocking in multi-mode fibers.

<u>Claims 55-57</u>

The Examiner rejects Claims 55-57 based on Wyatt in view of Fermann I or Kim (U.S. Patent No. 4,832,437). Independent Claim 55 is a method including, among other limitations, "amplifying said light energy within said laser cavity in a bent multi-mode fiber." The Examiner admits that Wyatt does not disclose bending the multi-mode fiber. Applicant respectfully

submits that Wyatt strongly teaches away from bending multi-mode fiber, because bent multi-mode fiber causes "significant coupling of power into higher order modes." Col. 7, l. 4-5 and 57-60. Such mode coupling makes it "difficult to control the amount of optical energy that exists in any single mode at any given time." Col. 6, l. 67-68. To avoid mode-coupling, the multi-mode fiber in Wyatt is "nominally straight" and has a length of at most one meter. Col. 7, l. 1-5 and 57-60. Wyatt states that any imperfections in the fiber can cause intermode coupling and greatly reduce the length the fundamental mode can travel without coupling to higher order modes. Col. 7, l. 60-66. Thus, a person of ordinary skill would read Wyatt as disclosing, at most, use of very short lengths of very straight multi-mode fiber to avoid coupling optical energy into higher order modes.

Applicant notes that if the proposed modification or combination of the prior art would (i) change the principle of operation of the prior art invention being modified or (ii) would render the prior art invention being modified unsatisfactory for its intended purpose, then the teachings of the references are not sufficient to render the claims *prima facie* obvious. M.P.E.P. 2143.01. The proper inquiry is "whether there is something in the prior art as a whole to suggest the *desirability*, and thus the obviousness, of making the combination." M.P.E.P. 2143.01 (emphasis in original).

Applicant respectfully submits that bending the straight, multi-mode fiber in Wyatt would cause coupling of energy into high order modes and thereby change Wyatt's principle of operation and intended purpose to enable stimulated emission "in *only* the fundamental mode." See, Wyatt Abstract (emphasis added). Additionally, Wyatt's teaching that multi-mode fiber should be straight (e.g., to avoid intermode coupling) strongly suggests that *bent* multi-mode fiber is undesirable. Accordingly, a person of ordinary skill would not be motivated to combine the teachings of Wyatt with *any* references (including, e.g., Fermann I and/or Kim) teaching or suggesting bending the optical fiber. Therefore, for at least this reason, Applicant respectfully submits that the Examiner has not established a *prima facie* case of obviousness for independent Claim 55.

Applicant notes that if "an independent claim is nonobvious under 35 U.S.C. 103, then any claim depending therefrom is nonobvious." M.P.E.P. 2143.03, citing *In re Fine*, 837 F.2d 1071, 1076 (Fed. Cir. 1988). Accordingly, Applicant respectfully submits that for at least this

reason the obviousness rejections of Claims 56 and 57, which depend from independent Claim 55, are improper.

Additionally, Applicant respectfully disagrees with the appropriateness of the Examiner's combination of the cited references. For example, Fermann I discloses bending a fiber with a *single-mode* core to reduce environmentally-induced nonlinear polarization changes in the fiber. Since the Examiner admits that Wyatt does not disclose bending a *multi-mode* fiber, the combination of Wyatt and Fermann I, even if appropriate, does not teach or suggest at least a bent multi-mode fiber as recited in Claims 55-57.

The Examiner further contends that Kim discloses coiling multi-mode fiber to strip light in higher order modes without stripping light in the fundamental mode. Applicant respectfully points out that to the extent Kim teaches or suggests a coiled multi-mode fiber as a mode stripper, the coiled multi-mode fiber is not disposed "within said laser cavity" (see, e.g., Fig. 9). Also, Kim does not teach or suggest that the mode stripper may be used for "confining said light energy within said laser cavity substantially to the fundamental mode of said multi-mode fiber" as recited in Claims 55-57. Accordingly, the combination of Wyatt and Kim does not teach or suggest each of the limitations in Claims 55-57.

Moreover, Applicant points out that rather than disclosing apparatus or methods usable with a laser or a laser cavity, Kim discloses an inter-propagation mode frequency shifter for an optical signal in a fiber. See, e.g., Abstract; Summary of the Invention, col. 2, l. 28-34; col. 5, l. 20-26; l. 52-57. Kim's disclosure does not relate to laser but rather to devices such as fiber optic gyros. See, col. 1, l. 25. Applicant respectfully submits that the Examiner has not identified a suggestion or motivation why a person of ordinary skill would combine Wyatt's teaching on lasers with Kim's teachings on frequency shifters for gyros or, even if combined, why there would be a reasonable expectation of success.

Additionally, Kim discloses coiling a single-clad, *double-mode* fiber (col. 19, l. 40) "to strip light propagating in the *second order mode* from the fiber without affecting the light propagating in the first order mode." Col. 5, l. 36-45 (emphasis added). Applicant respectfully submits that one of ordinary skill would recognize that a general multi-mode fiber typically has a much higher level of mode coupling than is present in Kim's double-mode fiber. For example, certain multi-mode fibers usable with the present invention are capable of propagating from 3 to

3000 modes. See, present application, paragraph [0047] as amended; Fermann II, col. 7, l. 12-14. Therefore, even assuming that it is appropriate to combine Wyatt's teaching of a straight multi-mode fiber with Kim's teaching of a coiled mode-stripper for second-order modes, the Examiner has not established that the combination provides a reasonable expectation of success for stripping *higher-order* modes, which may number in the thousands. Thus, the proposed combination of Wyatt and Kim at least does not teach or suggest "confining said light energy within said laser cavity substantially to the fundamental mode of said multi-mode fiber." Accordingly, Applicant respectfully submits the combination of Wyatt and Kim is improper.

The Examiner admits that Wyatt in view of Fermann I or Kim does not disclose mode locking light energy as recited in Claim 56. The Examiner contends that Fermann I discloses modelocking; however, as discussed above, to the extent Fermann I discloses modelocking, it is in the context of *single-mode* fibers and not *multi-mode* fibers as recited in Claim 56. Accordingly, not only does the combination of references fail to teach or suggest all the claim limitations, a person of ordinary skill would have no motivation to combine these references in order to achieve modelocking in *multi-mode* fibers, which, as of the filing date, was considered to be "impossible" as discussed above.

DOUBLE PATENTING

The Examiner has rejected Claims 1-8, 10, 11, 13-26, 30-33, 35-46, 50, and 55-57 on the ground of nonstatutory obviousness-type double patenting with respect to the Fermann II patent (U.S. Pat. No. 5,818,630) and the Fermann III patent (U.S. Pat. No. 6,275,512). Applicant respectfully disagrees that any of the claims of the present application are anticipated by, or would have been obvious over, the claims of either the Fermann II or Fermann III patents.

Applicant notes that nonstatutory double patenting requires a comparison of earlier *claims* to later *claims* and not a comparison of the *disclosures*. "Because nonstatutory double patenting compares earlier and later claims, an earlier patent's disclosure is not available to show nonstatutory double patenting. Of course, the earlier patent's disclosure may register on the patentability scale if that patent qualifies as prior art under 35 U.S.C. § 102, which is generally not the case." See, *Geneva Pharmaceuticals, Inc. v. GlaxoSmithKline PLC*, 349 F.3d 1373,

1385 (Fed. Cir. 2003); see, also, *In re Vogel*, 422 F.2d 438, 441 (CCPA 1970) ("the patent disclosure may not be used as prior art.).

Moreover, in analyzing possible double patenting, claims must be read "as a whole," with every limitation being material. See, *General Foods Corp. v. Studiengesellschaft Kohle mbH,* 972 F.2d 1272, 1278, 1280 (Fed. Cir. 1992). "[I]t is important to bear in mind that comparison can be made only with what invention is *claimed* in the earlier patent, paying careful attention to the rules of claim interpretation to determine what invention a claim *defines* and not looking to the claim for anything that happens to be mentioned in it as though it were a prior art reference." *Id.* at 1280 (emphasis in original). There can be no double patenting if the *inventions* defined in the claims are patentably distinct. *Id.* at 1278.

Fermann II

As discussed above, Applicant notes that Fermann II is not prior art under 35 U.S.C. § 102, because the claims of the present application derive from the work of Martin E. Fermann, a co-inventor of the Fermann II patent (see attached 1.132 declaration). Therefore, only the claims, and not the disclosure, of the Fermann II patent are available for the nonstatutory obviousness-type double patenting analysis.

The Examiner asserts that Claim 25 of Fermann II anticipates Claim 1 of the present application. Applicant respectfully submits that Claim 25, which is directed to an optical amplification system, defines *a different invention* than Claim 1, which is directed to a laser. For at least this reason, the double patenting rejection is improper. Additionally, Applicant notes that Claim 25 does not disclose all the limitations of Claim 1, such as, for example, "a cavity which repeatedly passes light energy along a cavity axis." Accordingly, Claim 25 of Fermann II does not anticipate Claim 1 of the present application.

Applicant further submits that the other claims of Fermann II do not define the same inventions (or an obvious variant) as defined in the claims of the present application. For example, Claim 1 recites "a pump coupled to said cladding [of a multi-mode fiber] for exciting said gain medium," which is not taught or suggested by the inventions defined by the Fermann II claims.

The Examiner asserts that Claim 25, "modified (and motivated) by the prior art applied above (under the 102 and 103 rejections), if necessary, renders obvious the remaining claims." Applicant respectfully submits that the Examiner's mere assertion of obviousness, without

additional evidence, cannot establish a *prima facie* case of nonstatutory obviousness-type double patenting. See, *In re Kaplan*, 789 F.2d 1574, 1580 (Fed. Cir. 1986) ("there must be some clear evidence to establish why the variation would have been obvious").

Accordingly, Applicant respectfully contends that the Examiner has not shown that the claims of the present application are anticipated by or rendered obvious over the claims of Fermann II. Applicant respectfully submits that the claims of the present application define inventions that are patentably distinct from the inventions defined in the Fermann II claims and respectfully requests the Examiner to withdraw the double patenting rejection based on the Fermann II patent.

Fermann III

The present application is a continuation of the application which issued as the Fermann III patent. Both the application and the patent have the same inventor: Martin E. Fermann. Therefore, the Fermann III patent is not Section 102 prior art to the present application and, for reasons similar to those discussed above for Fermann II, the disclosure of the Fermann III patent cannot be used as prior art in the nonstatutory obviousness-type double patenting analysis.

The Examiner asserts that Claim 1 of Fermann III modified (and motivated) by Fermann I to include a mode filter would render obvious Claim 55 of the present application. The Examiner also asserts that the other application claims would be obvious in view of the cited art (without providing any evidence or analysis).

Applicant respectfully notes that Claims 1-4 of Fermann III (the only claims in the patent) are directed to methods of generating ultra-short *pulses* (with peak power above 1kW), whereas Claims 55-57 are directed to *continuous wave* (cw) methods. Accordingly, the inventions defined by the claims of Fermann III and the present application are patentably distinct, because it is well recognized by persons of ordinary skill that pulsed and continuous wave optical amplification methods are substantially different. Additionally, Applicant submits that the double patenting rejections of Claims 1-8, 10, 11, 13-26, 30-33, 35-46, and 50 of the present application are improper. These claims define inventions of laser *apparatus* and are clearly patentably distinct from the ultra-short pulse generation *method* inventions defined by the

Fermann III claim, which are in an entirely different statutory class of invention. For at least these reasons, the double patenting rejection based on Fermann III is improper.

Applicant further submits that the combination of the Fermann III claims and the Fermann I patent is not appropriate. As discussed above, Fermann I discloses a single-mode fiber and does not teach or suggest multi-mode fibers as recited in the present application's claims. The Examiner has not identified a suggestion or motivation to combine these references or that the combination would give rise to a reasonable expectation of success. Moreover, Applicant submits that, even if combined, the combination does not teach or suggest at least all the limitations of Claims 55-57, such as, for example, "amplifying said light energy within said laser cavity in a bent multi-mode fiber."

Accordingly, Applicant respectfully contends that the Examiner has not shown that the claims of the present application are anticipated by or rendered obvious over the claims of Fermann III in view of the cited art. Applicant respectfully submits that the claims of the present application define inventions that are patentably distinct from the inventions defined in the Fermann III claims and respectfully requests the Examiner to withdraw the double patenting rejection based on the Fermann III patent.

AMENDMENT TO THE SPECIFICATION

Applicant amends the first paragraph of the section entitled "DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT" (paragraph [0047] as published) as indicated herein. The added material relates to the V-value and number of propagating modes in multi-mode fiber and is taken verbatim from U.S. Patent No. 5,818,630 (Fermann II), which is incorporated by reference in paragraph [0009] of the present application. The material added from Fermann II includes one sentence from col. 3, l. 12-15 and one sentence from col. 7, l. 12-14. No new matter is added by this amendment.

NEW CLAIMS

New claims 59-66 are added herein. Support for these claims is found at least in paragraph [0047] as amended herein. No new matter is added.

<u>SUMMARY</u>

Accordingly, Applicant respectfully submits that all of the pending claims are in condition for allowance and requests the present application be passed to issue.

By making the foregoing amendments and remarks and by focusing on specific claims and claim limitations in the discussion above, Applicant does not imply agreement with the positions set forth in the Office Action regarding other claims or claim limitations or the teachings of the cited art. Applicant also does not imply agreement with the positions in the Office Action that various combinations of the cited art are suggested or motivated by the prior art, have a reasonable expectation of success, or teach or suggest all the claim limitations.

Please charge any additional fees, including any fees for additional extension of time, or credit overpayment to Deposit Account No. 11-1410.

Respectfully submitted,

KNOBBE, MARTENS, OLSON & BEAR, LLP

Dated: 12/21/2006

By: Steven P. Ruden

Steven P. Ruden, Ph.D.
Registration No. 53,538
Attorney of Record
Customer No. 20,995
(949) 760-0404

Attachments: Exhibits 1-5
Declaration under 37 C.F.R. § 1.132 of Martin E. Fermann and Donald J. Harter

Appl. No. : **09/785,944**
Filed : **February 16, 2001**

EXHIBIT 1

SPONSORED BY THE

OPTICAL SOCIETY OF AMERICA

HANDBOOK OF OPTICS

DEVICES, MEASUREMENTS, & PROPERTIES

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VOLUME II

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published several books on fiber optics. The interested reader is referred to the "Further Reading" section at the end of this chapter for additional reference material.

Optical fiber science and technology relies heavily on both geometrical and physical optics, materials science, integrated and guided-wave optics, quantum optics and optical physics, communications engineering, and other disciplines. Interested readers are referred to other chapters within this collection for additional information on many of these topics.

The applications which are discussed in detail in this chapter are limited to information technology and telecommunications. Readers should, however, be aware of the tremendous activity and range of applications for optical fibers in metrology and medicine. The latter, which includes surgery, endoscopy, and sensing, is an area of tremendous technological importance and great recent interest. While the fiber design may be quite different when optimized for these applications, the general principles of operation remain much the same. A list of references which are entirely devoted to optical fibers in medicine is listed in "Further Reading".

10.3 PRINCIPLES OF OPERATION

The optical fiber falls into a subset (albeit the most commercially significant subset) of structures known as dielectric optical waveguides. The general principles of optical waveguides are discussed elsewhere in Chap. 6 of Vol. II, "Integrated Optics"; the optical fiber works on principles similar to other waveguides, with the important inclusion of a cylindrical axis of symmetry. For some specific applications, the fiber may deviate slightly from this symmetry; it is nevertheless fundamental to fiber design and fabrication. Figure 1 shows the generic optical fiber design, with a core of high refractive index surrounded by a low-index cladding. This index difference requires that light from inside the fiber which is incident at an angle greater than the critical angle

$$\theta_c = \sin^{-1}\left(\frac{n_1}{n_0}\right) \tag{1}$$

be totally internally reflected at the interface. A simple geometrical picture appears to allow a continuous range of internally reflected rays inside the structure; in fact, the light (being a wave) must satisfy a self-interference condition in order to be trapped in the waveguide. There are only a finite number of paths which satisfy this condition; these are analogous to the propagating electromagnetic modes of the structure. Fibers which support a large number of modes (these are fibers of large core and large numerical aperture) can be adequately analyzed by the tools of geometrical optics; fibers which support a small

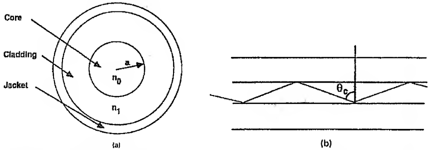

FIGURE 1 (a) Generic optical fiber design, (b) path of a ray propagating at the geometric angle for total internal reflection.

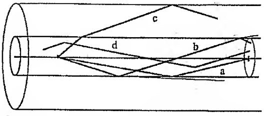

FIGURE 4 Classification of geometrical ray paths in an optical fiber. (*a*) Meridional ray; (*b*) leaky ray; (*c*) ray corresponding to a cladding mode; (*d*) skew ray.

laser-fiber coupling. A larger core and larger numerical aperture will, in general, yield a higher coupling efficiency. Coupling between fibers which are mismatched either in core or numerical aperture is difficult and generally results in excess loss.

The final concept for which a geometrical construction is helpful is ray classification. Those geometrical paths which pass through the axis of symmetry and obey the self-interference condition are known as *meridional rays*. There are classes of rays which are nearly totally internally reflected and may still propagate some distance down the fiber. These are known as *leaky rays* (or modes). Other geometrical paths are not at all confined in the core, but internally reflect off of the cladding-air (or jacket) interface. These are known as *cladding modes*. Finally, there exists a class of geometrical paths which are bound, can be introduced outside of the normal numerical aperture of the fiber, and do not pass through the axis of symmetry. These are often called *skew rays*. Figure 4 illustrates the classification of geometrical paths.

Geometrical optics has a limited function in the description of optical fibers, and the actual propagation characteristics must be understood in the context of guided-wave optics. For waveguides such as optical fibers which exhibit a small change in refractive index at the boundaries, the electric field can be well described by a scalar wave equation,

$$\nabla^2\Psi(r, \theta, z) + k_0^2 r^2(r)\Psi(r, \theta, z) = 0 \tag{2}$$

the solutions of which are the modes of the fiber. $\Psi(r, \theta, z)$ is generally assumed to be separable in the variables of the cylindrical coordinate system of the fiber:

$$\Psi(r, \theta, z) = R(r)\Theta(\theta)Z(z) \tag{3}$$

This separation results in the following eigenvalue equation for the radial part of the scalar field:

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left(k_0^2 n^2(r) - \beta^2 - \frac{m^2}{r^2}\right)R = 0 \tag{4}$$

in which m denotes the azimuthal mode number, and β is the propagation constant. The solutions must obey the necessary continuity conditions at the core-cladding boundary. In addition, guided modes must decay to zero outside the core region. These solutions are readily found for fibers having uniform, cylindrically symmetric regions but require numerical methods for fibers lacking cylindrical symmetry or having an arbitrary index gradient. A common form of the latter is the so-called *α-profile* in which the refractive index exhibits the radial gradient[4]

$$m(r) = \begin{cases} n_1\left[1 - \Delta\left(\frac{r}{a}\right)^{\alpha}\right] & r < a \\ n_1[1 - \Delta] = n_2 & r \geq a \end{cases} \tag{5}$$

TABLE 1 Normalized Variables in the Mathematical Description of Optical Fibers

Symbol	Description
$k_0 = \frac{2\pi}{\lambda}$	Vacuum wave vector
a	Core radius
n_0	Core index
n_1	Cladding index
$\tilde{\beta} = \beta' + i\beta''$	Mode propagation constant
$\alpha = 2\beta''$	Fiber attenuation
$N_{\text{eff}} = \beta'/k_0$	Effective index of mode
$\Delta = \frac{n_0^2 - n_1^2}{2n_1^2}$	Normalized core-cladding index differences
$V = \sqrt{2}k_0\, an_1\Delta$	Normalized frequency
$b = \left(\frac{N_{\text{eff}}}{n_1} - 1\right)\Big/\Delta$	Normalized effective index
$f(r)$	Gradient-index shape factor
$\Gamma = \frac{\int_0^a f(r)\Psi^2(r)r\,dr}{\int_0^a \Psi^2(r)r\,dr}$	Profile parameter ($\Gamma = 1$ for step-index)

of 1.3 to 1.55 μm. Shorter wavelengths will typically support two or more modes, resulting in significant intermodal interference at the output. In order to guarantee single-mode performance, it is important to determine the single-mode cut-off wavelength for a given fiber. Normalized variables allow one to readily determine the cut-off wavelength and dispersion limits of a fiber using universal curves.

The normalized variables are listed in Table 1 along with the usual designations for fiber parameters. The definitions here apply to the limit of the "weakly guiding" fiber of Gloge,[7] for which $\Delta \ll 1$. The cutoff for single-mode performance appears at a normalized frequency of $V = 2.405$. For values of V greater than this, the fiber is multimode. The practical range of frequencies for good single-mode fiber operation lie in the range

$$1.8 < V < 2.4 \tag{11}$$

An analytic approximation for the normalized propagation constant b which is valid for this range is given by

$$b(V) \approx \left(1 - 1.1428 - \frac{0.996}{V}\right)^2 \tag{12}$$

Operation close to the cutoff $V = 2.405$ risks introducing higher-order modes if the fiber parameters are not precisely targeted. A useful expression which applies to step-index fibers relates the core diameter and wavelength at the single-mode cutoff[5]:

$$\lambda_{\text{cutoff}} = \left(\frac{\pi}{2.405}\right)(2a)n_0\sqrt{2\Delta} \tag{13}$$

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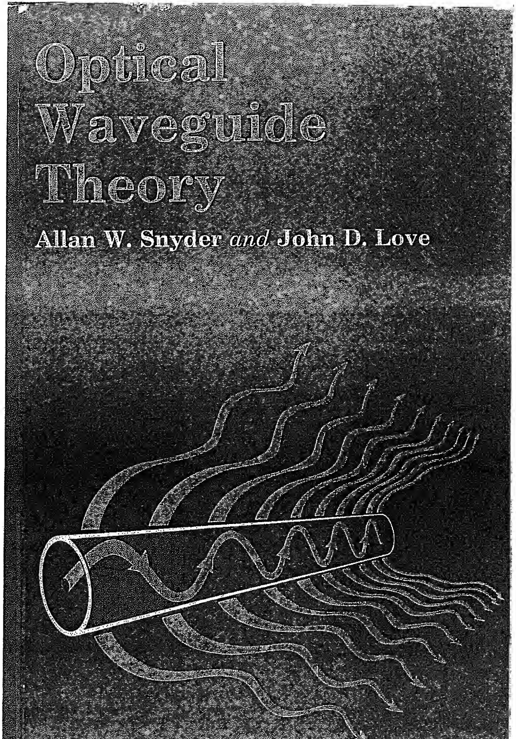
EXHIBIT 2



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CHAPTER 2

Bound rays of fibers

In Chapter 1 we established the basic concepts for the ray analysis of planar waveguides. Here we extend the analysis to optical fibers, which are used for high-capacity communication over long distances. As far as ray tracing is concerned, the only difference between fibers and planar waveguides is the introduction of the third dimension. Thus, although the ray concepts are the same as in Chapter 1, the analysis and resulting expressions are generally more complicated because of the fiber geometry. Nevertheless, one of the important results of this chapter shows that the ray transit times for step and clad power-law profile fibers of both circular and noncircular cross-sections are identical to

those of the corresponding planar waveguides. If this remarkable simplification is acceptable without proof, then pulse spreading in such fibers can be studied directly by proceeding to Chapter 3 and omitting this chapter at a first reading.

Most of the chapter is devoted to the construction of ray paths and their classification on circular fibers with axisymmetric profiles. However, we also consider noncircular fibers since cross-sections can differ from circular symmetry in practice, e.g. elliptical fibers. Finally, since this chapter parallels Chapter 1 to a large extent, it may be helpful to compare the results of corresponding sections.

2–1 Circular fibers

An optical fiber is illustrated in Fig. 2–1. Unless otherwise stated, the *core* is assumed to have a circularly symmetric cross-section of radius ρ, surrounded by the *cladding*, which, for simplicity, is assumed unbounded. The *core–cladding interface* is the cylindrical surface $r = \rho$. Over the core, the axisymmetric refractive-index profile $n(r)$ is either uniform or graded, and it takes the uniform value n_{cl} in the cladding.

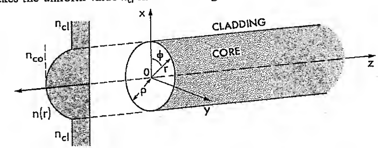

Fig. 2–1 Nomenclature for describing circular fibers. Cartesian coordinates x, y, z and cylindrical polar coordinates r, ϕ, z are oriented so that the z-axis lies along the fiber axis. A representative graded profile varies over the core and is uniform over the cladding, assumed unbounded.

The dimensionless parameter V of Eq. (1–1) also applies to fibers, and will be referred to as the *fiber parameter*. Thus

$$\boxed{V = \frac{2\pi\rho}{\lambda}\left(n_{co}^2 - n_{cl}^2\right)^{1/2},} \tag{2–1}$$

where n_{co} is the maximum value of $n(r)$, ρ the core radius, and λ the free-space wavelength of light. The quantity $(n_{co}^2 - n_{cl}^2)^{1/2}$ is often referred to as the *numerical aperture* of the fiber, while a related expression $\{n^2(r) - n_{cl}^2\}^{1/2}$ is

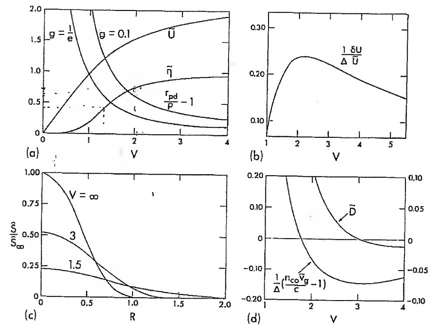

Fig. 14-3 Fundamental mode quantities for the step-profile fiber, showing (a) the modal parameter $\tilde{U}$, the fraction of power in the core $\tilde{\eta}$, and the depth of penetration r_{pd}, (b) the normalized polarization correction $\delta U/\Delta\tilde{U}$, (c) the normalized intensity distribution and (d) the normalized variation in group velocity relative to the left ordinate, and the distortion parameter $\tilde{D}$ relative to the right ordinate. Numerical values are given in Table 14-4.

Depth of penetration of the field intensity

The fundamental-mode intensity in Fig. 14–3(c) can be significant well into the cladding. At sufficiently large distances from the axis it decreases exponentially with R, as is clear from Table 14–3 and Eq. (37–88). To quantify the size of this region, we define r_{pd} to be the distance from the fiber axis where S has fallen to a factor $g < 1$ of its value at the interface. Thus

$$K_0^2(\tilde{W} r_{pd}/\rho) = g K_0^2(\tilde{W}). \tag{14–18}$$

The normalized distance $(r_{pd}/\rho) - 1$ from the interface is a measure of the effective depth of penetration of the core field into the cladding. We plot this quantity as a function of V in Fig. 14–3(a), taking $g = e^{-1}$ for the lower curve and $g = 0.1$ for the upper curve. For example, when $V = 2.5$ we deduce from the $\tilde{\eta}$ curve that about 84% of total fundamental-mode power flows within the core, and the intensity, or power density, falls by a factor of e^{-1} over a distance of approximately $\rho/2$ beyond the interface.

Pulse propagation and spreading

If V is below the cutoff value 2.405 of the second mode in Fig. 14–4, the fiber is single moded and only the even and odd fundamental modes can propagate. Both modes have the same propagation constant $\tilde{\beta}$. Consequently the group velocity $\tilde{v}_g$ and the transit time of Eq. (11–36) are independent of polarization. In the weak-guidance approximation, the expression for $\tilde{v}_g$ in Table 14–3 follows from Eq. (13–17), and is plotted against V in Fig. 14–3(d) as the dimensionless quantity $(n_{co}\tilde{v}_g - c)/c\Delta$.

Pulse spreading on single-mode fibers depends only on waveguide dispersion and material dispersion, as discussed in Section 11–12. The contribution to pulse spreading in the absence of material dispersion is proportional to the dimensionless distortion parameter introduced in Section 11–20. Using the definition $\tilde{D}$ for weakly guiding fibers in Table 13–2, page 292, we are led to the expression in Table 14–3. Numerical values of D are given in Table 14–4 and are plotted in Fig. 14–3(d). There is zero waveguide dispersion at $V \cong 3$, which corresponds to the minimum group velocity value.

Approximate forms for large and small values of V

It is often useful to have approximations to the fundamental-mode properties in Table 14–3 when V is either large or small. These approximations are given in Table 14–5. The expressions for the modal parameters are the $\Delta \to 0$ limit of the expression in Table 12–4, page 253, where we have used the small argument expression of J_v in Eq. (37–82). The remaining expressions in Table 14–5 are obtained from Table 14–3 by using the expansions of K_0 and K_1 in Eqs. (37–86) and (37–88) for small and large arguments, and assuming $\tilde{U} \cong V$ if V is small or $\tilde{W} \cong V$ if V is large. The accuracy of each approximation can be gauged by comparison with the exact values in Table 14–4 for $V = 1.05$ or $V = 4$. For intermediate values of V, an excellent approximation can be derived by assuming $\tilde{W}$ is a linear function of V. This leads to [5].

$$\tilde{W} = 1.1428\, V - 0.996, \quad 1.5 \leqslant V \leqslant 2.5, \tag{14–19}$$

which is within 0.2% of the exact values over the range. However, derivatives of this expression do not usually lead to expressions for group velocity and the distortion parameter with the same accuracy [6].

14–7 Higher-order ($l \geqslant 1$) modes

The construction of the remaining modes of the fiber was described in Section 14–3. We give the solution F_l of Eq. (14–4) and the functions $G_l^{\pm}$ in Table 14–6

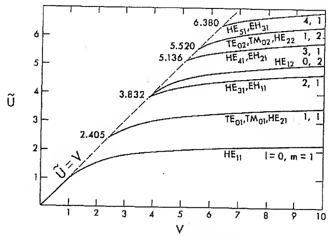

Fig. 14–4 Numerical solutions of the eigenvalue equation of Table 14–6, showing the mode labelling and the corresponding values of l and m. The values along the dashed line are the cutoff values V_c for each mode.

Mode cutoff

With the exception of the fundamental HE_{11} mode, every mode is cut off below a certain value of V and cannot propagate, as explained in Section 11–18. The cutoff value of $\tilde{U}$ is the eigenvalue equation solution in the limit $\tilde{W} \to 0$. With the help of Eq. (37–86), we deduce that $J_{l-1}(\tilde{U}) = 0$ for all modes, including the HE_{1m} modes ($m > 1$) for which $J_1(\tilde{U}) = 0$. This leads to the cutoff values in Fig. 14–4, from which we find that the fiber is single-moded if $V < 2.405$, where $\tilde{U} = V \cong 2.405$ is the cutoff value of the $l = m = 1$ modes. When $\tilde{W} \cong V \to \infty$, we find from the eigenvalue equation and Eq. (37–88) that $\tilde{U}$ satisfies $J_l(\tilde{U}) = 0$. It is readily verified that these limiting equations are the weak-guidance limit of the expressions in Table 12–4, page 253.

Polarization corrections

The corrections $\delta\beta_i$ to the scalar propagation constant are given in Table 14–1 in terms of I_1 and I_2. In the numerator of each expression, the derivative df/dR is the Dirac delta function $\delta(R-1)$, as explained in Section 14–6, and the integral in the denominator is given in Table 14–6. This leads to the expressions for $\delta\beta_i$ and the corresponding δU_i in the same table. There is no correction for the TE_{0m} modes, whose fields satisfy the scalar wave equation exactly.

We plot the ratio $\delta U/\Delta\tilde{U}$ in Fig. 14–5(a) for the TM_{01} mode, which has a maximum value of approximately 0.22 when $V \cong 5$. If we compare the corrected mode parameter $\tilde{U} + \delta U$ with the exact value of U of the TM mode eigenvalue equation in Table 12–4, page 253, the maximum relative error is less than 0.005% for $\Delta = 0.005$ and rises to 0.05% and 0.41% for $\Delta = 0.045$ and $\Delta = 0.125$, respectively.

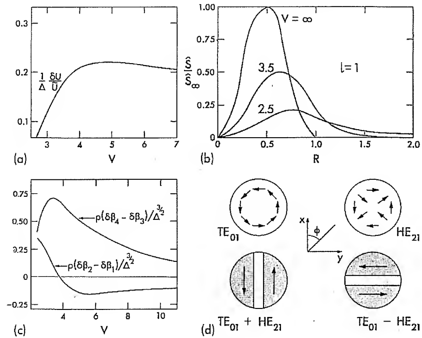

Fig. 14–5 Plots of $l = 1$ mode quantities for the step-profile fiber, showing (a) the normalized vector correction $\delta U/\Delta\tilde{U}$ for the TM_{01} mode, (b) the normalized intensity distribution, (c) the difference in vector corrections for the two pairs of $l = 1$ modes and (d) qualitative representation of the transverse electric field direction, denoted by arrows.

Interference between modes

The finite propagation constant corrections $\delta\beta_i$ discussed above are responsible for interference effects between pairs of modes with the same scalar propagation constant. For example, suppose the odd HE_{21} and TE_{01} modes are excited with equal power and all other modes have zero power. If we erroneously ignore all polarization effects, then $\delta\beta_3 = \delta\beta_4 = 0$, and the total transverse electric field of the fiber follows from Table 14–1 as

$$\mathbf{E}_t = a\mathbf{e}_{t3}\exp(i\tilde{\beta}z) + a\mathbf{e}_{t4}\exp(i\tilde{\beta}z) = 2aF_l \sin\phi \exp(i\tilde{\beta}z)\hat{\mathbf{x}}, \qquad (14–20)$$

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Filed : February 16, 2001

EXHIBIT 3

TOOLS OF THE TRADE

THORLABS INC

VOLUME 17

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Highly Doped Ytterbium Fibers

The Yb2000 family of very highly doped ytterbium fibers is designed for those applications where extremely short fiber application length is must, such as advanced pulsed applications or applications where non-linear effects must be minimized. These fibers, fabricated using Liekki's Direct Nanoparticle Deposition (DND) technology, seek to maximize the doping density without sacrificing useability.

Yb2000-4/125

Liekki Yb2000-4/125 is a very highly doped ytterbium fiber for low noise, low non-linearity preamplifiers and lasers. Its telecom like geometry makes the fiber compatible with low cost pump diodes and standard single mode passive fibers.

Optical Characteristics:
- Peak absorption at 976nm: 2000 ± 200dB/m
- Peak absorption at 920nm: 600 ± 60dB/m
- Mode field diameter at 1060nm: 4.4 ± 0.8µm
- Core numerical aperture: 0.2 ± 0.02
- Fiber cutoff wavelength: < 920nm

Geometrical Characteristics:
- MDF concentricity error: < 0.7µm
- Cladding diameter: 125 ± 2µm
- Coating diameter: 245 ± 15µm

Yb2000-6/125DC

Liekki Yb2000-6/125DC is a very highly doped ytterbium double clad fiber for low cost single mode lasers and preamplifiers in the 1…10W output power range. Its telecom like geometry makes the fiber compatible with low cost pump diodes and standard single mode passive fibers.

Optical Characteristics:
- Cladding absorption at 976nm (nominal): 5 dB/m
- Cladding absorption at 920nm: 1.5 ± 0.5dB/m
- Mode field diameter at 1060nm: 6.7 ± 0.8µm
- Core numerical aperture: 0.12 ± 0.02

Geometrical Characteristics:
- Cladding diameter: 125 ± 2µm
- Cladding numerical aperture: > 0.46
- Coating diameter: 245 ± 15µm
- Coating material: low index polymer

Yb2000-30/400DC

Yb2000-30/400DC is very highly doped large mode area double clad fiber for high power fiber applications. High absorption makes this fiber ideally suited for pulsed applications, as fiber application lengths can be dramatically shortened. This fiber has high power tolerance and good beam quality.

Optical Characteristics:
- Cladding absorption at 976nm (nominal): 10 dB/m
- Cladding absorption at 920nm: 3 ± 0.5dB/m
- Core numerical aperture: 0.07 ± 0.01

Geometrical Characteristics:
- Core diameter: 30 ± 3µm
- Cladding diameter: 400 ± 15µm
- Cladding numerical aperture: > 0.46
- Coating diameter: 500 ± 15µm
- Coating material: low index polymet

Single mode Yb doped fiber specifications

ITEM	ABSORPTION @976nm	ABSORPTION @920nm	MFD @1060nm	NA CORE	CLADDING DIAMETER	COATING DIAMETER	NA CLADDING
Yb1200-4/125	1200 ± 200dB/m	300 ± 50dB/m	4.4 ± 0.8µm	0.2 ± 0.02	125 ± 2µm	245 ± 15µm	N/A
Yb2000-4/125	2000 ± 200dB/m	600 ± 60dB/m	4.4 ± 0.8µm	0.2 ± 0.02	125 ± 2µm	245 ± 15µm	N/A
Yb2000-6/125DC	5 dB/m (nominal)	1.5 ± 0.5dB/m	6.7 ± 0.8µm	0.12 ± 0.02	125 ± 2µm	245 ± 15µm	>0.46
Yb1200-10/125DC	7dB/m (nominal))	1.7 ± 0.5dB/m	10.5 ± 1µm	0.08 ± 0.01	125 ± 2µm	245 ± 15µm	>0.46

Multimode Yb doped fiber specifications

ITEM	ABSORPTION @976nm	ABSORPTION @920nm	CORE DIAMETER	NA CORE	CLADDING DIAMETER	COATING DIAMETER	NA CLADDING
Yb1200-20/400DC	3dB/m (nominal)	0.7 ± 0.2dB/m	20 ± 2µm	0.07 ± 0.01	400 ± 15µm	500 ± 15µm	>0.46
Yb1200-30/250DC	17dB/m (nominal)	4 ± 1dB/m	30 ± 3µm	0.07 ± 0.01	250 ± 15µm	350 ± 15µm	>0.46
Yb2000-30/400DC	10 dB/m (nominal)	3 ± 0.5dB/m	30 ± 3µm	0.07 ± 0.01	400 ± 15µm	500 ± 15µm	>0.46

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EXHIBIT 4

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Joseph C. Palais
Professor of Electrical Engineering
Arizona State University

PRENTICE HALL, Upper Saddle River, New Jersey 07458

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Chapter 5

Optic Fiber Waveguides

We are now ready to address the major item in our communications system, the optic fibers. Although only a few will ever design and fabricate your own fibers, you should have some idea how it is accomplished. Proper choice and proper utilization require a deep understanding of fiber construction and fiber characteristics. With this in mind, we will study the major types of fibers and the properties of waves propagating through them. We will pay particular attention to attenuation, modes, and information capacity. Construction and design of fibers and fiber cables are also discussed.

5-1 STEP-INDEX FIBER

The *step-index* (SI) fiber[1] consists of a central core whose refractive index is n_1, surrounded by a cladding whose refractive index is n_2. Figure 5-1 illustrates the structure, sometimes referred to as the *step-index matched-clad* fiber. As with the dielectric slab, complete guidance requires that the reflection angle θ be equal to or greater than the critical angle θ_c. The critical angle for the SI fiber is given by

$$\sin \theta_c = \frac{n_2}{n_1} \tag{5-1}$$

The *fractional refractive index change* Δ is an important fiber parameter. It is given by

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{5-2}$$

This parameter is always positive because n_1 must be larger than n_2 for a critical angle to exist. Typically, Δ is of the order of 0.01.

Efficient transmission requires that the core and cladding be as free of loss as possible. Although the ray diagram implies that the light travels entirely within the core, this is not precisely the case. Actually, some of the light travels in the cladding in the form of an evanescent wave, as discussed in Chapter 4 for the slab waveguide. If the cladding is nonabsorbent, then this light is not lost but travels along the fiber. The evanescent fields decay rapidly, so that no light will reach the edge of the cladding if it is a few tens of microns thick.

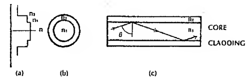

Figure 5-1 Step-index fiber. (a) Refractive index profile. (b) End view. (c) Cross-sectional side view.

The question arises as to the need for the cladding at all. A core of glass surrounded by air satisfies the requirement $n_1 > n_2$, and would indeed guide a light wave. However, severe problems arise when attempting to handle or support this type of structure. Any lossy material attached to the core for support will cause losses in the propagating wave. The freely suspended core could bend or be easily scratched, causing additional losses. The cladding protects the core from contamination and helps preserve its physical integrity.

Step-index fibers have three common forms: a glass core, cladded with a glass having a slightly lower refractive index; a silica glass core, cladded with plastic; and a plastic core, cladded with another plastic. Generally, the refractive-index step is smallest for all-glass fibers, a little larger for the plastic-cladded silica (PCS) fibers, and largest for the all-plastic construction. The all-plastic fiber is often referred to as *polymer optical fiber* (POF). The step sizes are due to the limited range of refractive indices available for glasses and the somewhat larger range for plastics.

As with the slab waveguide, modal distortion and numerical aperture increase with the refractive index difference, $n_1 - n_2$. Because of this, the intermodal pulse spread and NA are small for the all-glass fiber, larger for the PCS fiber, and highest for the all-plastic structure. Fibers with little pulse spread have large rate-length products. The NA of these fibers is small, making it difficult to efficiently couple light into them.

The attenuation loss in an all-glass fiber is generally lower than in a PCS or an all-plastic fiber. All-glass losses of a few dB/km and less are available. PCS fibers have losses around 8 dB/km. All-plastic fibers may have losses of several hundred dB/km.

From the information in the preceding paragraphs, we can reach a number of conclusions regarding the performance and applications of the three types of SI fibers. The following statements apply to fibers that are large enough to support many modes:

1. All-glass fibers have the lowest losses and the smallest intermodal pulse spreading. Because of these properties, they are useful at moderately high information rates or fairly long lengths. 30 MHz × km is an achievable rate-length product. The low NA of the SI glass fiber results in large losses when coupling from a light source. The low transmission loss partially compensates for this problem.

   Conventionally, the size of a fiber is denoted by writing its core diameter and then its cladding diameter (both in micrometers) with a slash between them. For example, a 50/125 fiber describes one with a 50-μm core and a 125-μm cladding. Typical dimensions of SI fibers are 50/125, 100/140, and 200/230.
2. Because PCS fibers have higher losses and larger pulse spreads than all-glass fibers, they are suitable for shorter links.

Their higher numerical apertures increase the source coupling efficiency, but this advantage is lost in a long fiber owing to increased absorption. PCS fibers are normally suitable choices when the path lengths are less than a few hundred meters. Core diameters of 200 μm are typical for PCS fibers. The large core diameter improves the source coupling efficiency.

3. All-plastic fibers are limited to very short paths by their high propagation losses. Path lengths are usually less than a few tens of meters. Large cores and large numerical apertures make plastic fibers usable because of the resulting high coupling efficiencies. Core diameters as large as 1 mm are typical.

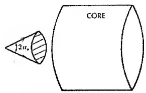

Figure 5-2 Acceptance cone for trapping of light by a step-index fiber.

Numerical apertures, acceptance angles, and fractional refractive-index changes for fibers representative of all-glass, PCS, and all-plastic constructions are listed in Table 5-1. The numerical apertures and acceptance angles were computed from Eq. (4-21), NA = $\sin \alpha_o = \sqrt{n_1^2 - n_2^2}$, assuming that air surrounded the input end of the fiber. Since the core and cladding refractive indices are nearly equal for most all-glass fibers, the approximate result NA = $n_1\sqrt{2\Delta}$ is valid for them. Only rays emitted within a cone having a full angle $2\alpha_o$ will be trapped by an SI fiber, as illustrated in Fig. 5-2. Typical LEDs and laser diodes emit light over a wide angular range, often larger than the acceptance angles in Table 5-1. The numerical results in Table 5-1 show the clear advantage of a fiber having a larger NA, and thus a larger acceptance angle, for improved light collection. In Section 8-5 we consider the source-fiber coupling losses quantitatively.

Review of the step-index structure indicates that light can also be trapped by total internal reflection at the outer boundary of the cladding if the material surrounding the cladding has a lower refractive index than the cladding itself. Figure 5-3 illustrates the possible ray paths. In the example shown, the ray angle at the core-cladding interface is less than the critical angle, so some light is transmitted into the cladding. This light strikes the outer surface of the cladding beyond the critical angle for that boundary and totally reflects back toward the fiber axis. The light represented by this ray never leaves the fiber and is thus guided by it. This example illustrates the existence of cladding modes. Cladding modes are characterized by rays traveling along paths that cross the fiber axis at angles greater than those of the modes guided by the core. They are excited by light introduced into the fiber end at angles beyond the acceptance angle. They also begin at discontinuities, such as splices and connectors, where light may be deflected beyond the core-mode angles.

TABLE 5-1. Typical Step-Index Fiber Characteristics

Construction	n_1	n_2	NA	α_o	Δ
All-glass	1.48	1.46	0.24	13.9°	0.0135
PCS	1.46	1.4	0.41	24.2°	0.041
All-plastic	1.49	1.41	0.48	29°	0.054

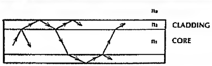

Figure 5-3 Ray paths of cladding modes. At the core-cladding interface there is partial reflection, accounting for the multiple ray paths.

The light traveling in a cladding mode attenuates more rapidly than light in a core mode because the outer boundary of the cladding is normally in contact with a lossy material. In addition, small bends in the fiber reduce the ray angle below that for total reflection, causing radiation losses. We can often observe power in cladding modes at points close to the light source. This power attenuates so rapidly that the cladding modes are insignificant at the end of a long fiber.

Example 5-1

Suppose that the glass fiber in Table 5-1 is surrounded by air. Compute the critical angle at the cladding-air boundary.

Solution:

Again by using the critical-angle equation, we find $\theta_c = \sin^{-1}(1/1.46) = 43°$. This should be compared with a core mode, where $\theta_c = \sin^{-1}(1.46/1.48) = 80.6°$. Recalling that θ is the ray angle as measured from the boundary normal, we can see how much more steeply the cladding-mode rays travel, relative to the fiber axis, than the core-mode rays.

Cladding modes are eliminated in some fibers by coating the cladding with a material having a refractive index equal to, or greater than, that of the cladding itself. In such a fiber, referred to as one with a *matched buffer*, a critical angle does not exist at the outer boundary of the cladding.

5-2 GRADED-INDEX FIBER

The *graded-index* (GRIN) fiber has a core material whose refractive index decreases continuously with distance from the fiber axis. This structure, illustrated in Fig. 5-4, appears to be quite different from the SI fiber. We will show how the GRIN fiber guides light by trapping rays, not unlike the operation of a SI waveguide. The index variation is described by[2]

$$n(r) = n_1\sqrt{1 - 2(r/a)^{\alpha}\Delta}, \quad r \leq a \tag{5-3a}$$

$$n(r) = n_1\sqrt{1 - 2\Delta} = n_2, \quad r > a \tag{5-3b}$$

where

n_1 = refractive index along the fiber axis
n_2 = refractive index outside the core (cladding index)
a = core radius
α = parameter describing the refractive-index profile variation
Δ = parameter determining the scale of the profile change

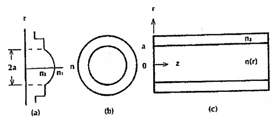

Figure 5-4 Graded-index fiber. (a) Refractive-index profile. (b) End view. (c) Cross-sectional view.

sures the location of splices, connectors, and breaks.

An example of a system power-budget calculation follows, although a more detailed system design discussion is presented in Chapter 12.

Example 5-4

A fiber system operates at a wavelength of 1300 nm where the fiber loss is 0.5 dB/km. The LED light source emits 1.59 mW and couples with a 16-dB loss into the fiber. Connectors and splices in the system contribute a total loss of 6 dB. The *receiver sensitivity* (the power required for the receiver to detect the message with a specified error rate or signal-to-noise ratio) is given as − 30 dBm. A 4-dB margin is specified to account for system degradations (such as aging of the LED). What is the maximum length of fiber that can be used?

TABLE 5-2. Sample Power-Budget Calculations

LED output power		2 dBm
Receiver sensitivity		− 30 dBm
Loss budget		32 dB
Coupling loss	16 dB	
Connector and splices	6 dB	
Power margin	4 dB	
Total losses	26 dB	− 26 dB
Available fiber loss		6 dB

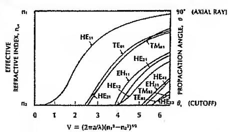

Figure 5-17 Mode chart for step-index fibers. (The HE_{11} mode cuts off at $V = 0$.) (From Donald B. Keck, "Optical Fiber Waveguides," in *Fundamentals of Optical Fiber Communications*, 2d ed., Michael K. Barnoski, ed., New York: Academic Press, Inc., 1981, p. 18. Reproduced with permission.)

Solution:

It is often convenient to perform power-budget calculations in dBm and dB. The LED power of 1.59 mW equals 2 dBm. Table 5-2 summarizes the power-budget calculations.

The maximum allowable fiber length is then 6/0.5 = 12 km.

5-4 MODES IN STEP-INDEX FIBERS

The mode chart for step-index fibers appears in Fig. 5-17. This chart is similar to the symmetrical slab mode chart in Fig. 4-5. One difference is that the fiber chart has been normalized by plotting the effective refractive index as a function of the parameter V. V, called the *normalized frequency*, is given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \qquad (5\text{-}7)$$

where a is the core radius and λ is the free-space wavelength. By using V, a single chart can be drawn that applies for any combination of values of a, λ, n_1, and n_2. As the propagation characteristics that can be deduced from the SI mode chart are discussed, note the many features common to wave travel in the fiber and in the slab.

The chart shows the existence of many modes. TE and TM modes are the transverse electric and transverse magnetic modes as defined in Section 4-2. HE and EH modes are hybrid, and both contain components of electric and magnetic fields pointing along the fiber axis. Each curve in Fig. 5-17 actually represents two modes, one orthogonally polarized with respect to the other in the transverse plane.

Conventional fibers do not preserve the polarization of the launched wave. Since orthogonally polarized waves associated with the same mode have the same effective refractive indices, they travel at the same velocity and easily couple energy between themselves. This exchange occurs at bends, twists, splices, and any other mechanical deformation of the fiber.

The effective refractive indices for all modes lie between the index of the cladding and that of the core. For a given mode, n_{eff} varies with wavelength, producing waveguide dispersion. At a fixed value of V, several modes may propagate, each having a different effective index. This condition leads to modal distortion. The longitudinal propagation factor can be obtained from n_{eff} by applying Eq. (4-6), $\beta = k_0 n_{eff}$. Ray angles are determined from Eq. (4-7).

Propagation in the fiber is quite similar to propagation in the slab. As with the slab, modes are cut off when their rays travel at the critical angle, and rays far from cutoff travel close to 90° almost directly down the fiber. In addition, decaying evanescent fields exist outside the core for all of the modes; and the closer a mode comes to cutoff, the deeper its wave penetrates into the cladding. Far from cutoff, a propagating wave travels almost entirely in the core.

For large values of V, many modes will propagate. Large V corresponds to a relatively large core radius. When $V > 10$, the number of modes (including all polarizations) is approximated by[6]

$$N = \frac{V^2}{2} \qquad (5\text{-}8)$$

Example 5-5

Compute the number of modes for a fiber whose core diameter is 50 μm. Assume that $n_1 = 1.48$ and $n_2 = 1.46$, as was done for the all-glass fiber in Section 5-1. Let $\lambda = 0.82\ \mu$m.

Solution:

The value of V, from Eq. (5-7), is

$$V = \frac{2\pi(25)}{0.82}\sqrt{1.48^2 - 1.46^2} = 46.45$$

Then, from Eq. (5-8), we find that there are 1078 modes.

It is clear from this example that even a moderately small fiber can support a large number of modes. Because the normalized frequency is proportional to the difference in refractive indices of the core and cladding, keeping this difference small reduces the number of propagating modes.

The lowest-ordered mode for the SI fiber is the HE_{11} mode. Its transverse field pattern, drawn in Fig. 5-18, is approximately Gaussian shaped. That is, the power distribution in the

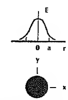

Figure 5-18 Transverse pattern for the lowest-ordered mode in the SI fiber, the HE_{11} mode.

transverse plane is approximated by the Gaussian intensity pattern given by Eq. (2-15). The Gaussian approximation is good when the V parameter is between 1.8 and 2.4, the region where (for reasons to be discussed in the next few paragraphs) most single-mode fibers are designed to operate.

The spot size (also frequently called the *mode-field radius*) of the equivalent Gaussian beam is given in terms of the normalized frequency by the expression[7]

$$\frac{w}{a} = 0.65 + 1.69V^{-3/2} + 2.879V^{-6} \qquad (5\text{-}9)$$

This expression, valid for the range $1.2 < V < 2.4$, is plotted in Fig. 5-19. Note that as the V parameter decreases below 2.4, the spot size increases and eventually becomes much larger than the core radius. In other words, for small values of V the light beam extends significantly beyond the core and into the cladding. In this condition the beam is not as tightly bound to the core and is highly susceptible to bending losses. For this reason, single-mode fibers are normally operated with a value of V in the neighborhood of 2–2.4. Values of V close to 2.4 are avoided to minimize the chances of propagation of more than just one mode.

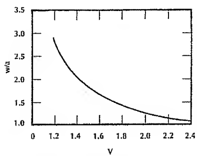

Figure 5-19 Normalized spot size w/a for the lowest-ordered mode in a step-index fiber.

Single-mode propagation is assured if all modes except the HE_{11} mode are cut off. Referring to Fig. 5-17, this occurs if $V < 2.405$. Combining this result with Eq. (5-7) yields

$$\frac{a}{\lambda} < \frac{2.405}{2\pi\sqrt{n_1^2 - n_2^2}} = \frac{2.405}{2\pi \cdot (NA)} \qquad (5\text{-}10)$$

as the condition for single-mode propagation. This result is very similar to the single-mode condition for the symmetrical slab, Eq. (4-17). If Eq. (5-10) is satisfied, then only the HE_{11} mode may travel through the fiber. Two orthogonally polarized HE_{11} waves can actually exist in the fiber simultaneously, but they have the same n_{eff} and, therefore, travel at the same velocity. This characteristic is more important than the fact that there are actually two modes in most applications.

An exception to this rule occurs when the fiber exhibits significant *birefringence*. Birefringence refers to the phenomenon where the refractive index depends on the direction of wave polarization. Birefringence occurs because of the lack of perfect circular symmetry in the refractive index. This lack of symmetry arises because the fiber may not be perfectly circular *(geometrical birefringence)* and because of unequal stresses built into the fiber *(stress birefringence)*. With birefringence the wave velocity *will* depend upon the direction of polarization. Thus the two orthogonally polarized HE_{11} waves will not travel at the same speed. This is a small effect in conventional single-mode fibers. It is enhanced in single-mode *polarization-preserving fibers*, which are designed to maintain the polarization of the launched wave. Polarization is preserved because the two possible waves have significantly different propagation characteristics. This keeps them from exchanging energy as they propagate through the fiber.

Polarization-preserving fibers are constructed by designing asymmetries into the fiber.[8] Examples include fibers with elliptical cores (which cause waves polarized along the major and minor axes of the ellipse to have different effective refractive indices) and fibers that contain nonsymmetrical stress-producing parts. These are illustrated in Fig. 5-20. The shaded region in the bow-tie fiber is highly doped with a material such as boron. Because the thermal expansion of this doped region is so different from that of the pure silica cladding, a nonsymmetrical stress is exerted on the core. This produces a large stress-induced birefringence, which in turn decouples the two orthogonal modes of the single-mode fiber.

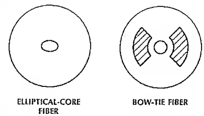

Figure 5-20 Polarization-preserving fibers.

Polarization-preserving fibers are required in several applications. These include the fiber optic gyroscope and coherent optical detection systems (these applications are discussed in Section 10-5).

Still another special fiber is the *polarizing fiber*. This single-mode fiber allows only one of the two orthogonally polarized HE_{11} modes to propagate. It does so by designing the asymmetry in the fiber such that the undesired polarization state has a higher attenuation than that of the desired state. These fibers can be used to produce polarized light when the source is unpolarized.

Polarization control in conventional, polarization-preserving, and polarizing fiber is illustrated in Fig. 5-21. In (a) a conventional fiber, the output polarization is unknown regardless of the input polarization state because of random coupling between all the polarizations present. In (b) a polarization-preserving fiber maintains the polarization of a polarized input wave but cannot polarize an incoming unpolarized beam. In (c) a polarizing fiber will pass just one of the polarizations present in an unpolarized input and will maintain the polarization of an input polarized in the preferred direction of the fiber polarizer. An input polarized in the nonpreferred direction will not be propagated.

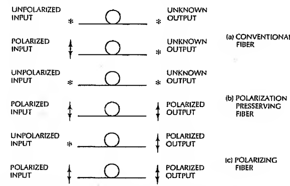

Figure 5-21 Polarizing effects of a conventional, polarization-preserving, and polarizing fiber.

EXHIBIT 5

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EDITED BY

PAUL F. LIAO
Bell Communications Research, Inc.
Red Bank, New Jersey

PAUL L. KELLEY
Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, Massachusetts

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To Haide, Christina and Mikel

2.2 Guided Modes of the Optical Fiber

All dielectric waveguides support a finite number of guided modes in addition to the infinite continuum of radiation modes that are not guided by the structure but are, nevertheless, solutions of the same boundary value problem. We begin the approximate analytical treatment of round optical fibers by deriving the guided modes of the structure.

Marcatili realized that the description of the modes of the weakly guiding fiber becomes much simpler if the components of the field vectors are expressed in rectangular cartesian coordinates instead of the cylindrical coordinates that appear so much more suitable to the cylindrical geometry of the waveguide.

The cross section of the optical fiber is shown in Fig. 2.2.1. Region 1 with refractive index n_1 is the fiber core, region 2 with index n_2 is the cladding. In all our work we assume that the cladding is infinitely extended, in spite of the fact that it has a finite radius for practical fibers. The justification for assuming an infinitely extended cladding region comes from the fact that the guided modes have exponentially decaying fields outside the core. If the cladding radius is large enough, the guided mode fields have decayed to insignificant values at the outer boundary of the cladding. All practical fibers are designed to ensure that the guided mode field does not reach the outer boundary of the cladding. In the opposite case the fiber would suffer high radiation losses, since the outer fiber surface is never perfectly smooth on account of accumulating dust and other environmental effects.

The assumption of an infinite cladding radius is more questionable when we study the radiation modes. These solutions of the boundary value problem

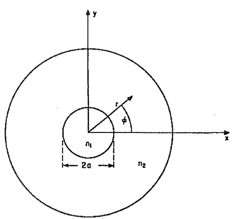

Fig. 2.2.1 *Cross section of a round optical fiber.*

reach out to infinity with undiminished strength and are certainly strongly affected by the outer cladding boundary. However, we can justify our procedure even for the radiation modes. The finite radius of the cladding has the effect of trapping some of the radiation field, causing cladding modes to appear. These modes have a discrete spectrum of allowed values of their propagation constants. But the density of these modes is much higher than the core modes, so that they form almost a continuum. When we calculate the interaction of the core modes with the radiation modes of the fiber with infinite cladding, we must keep in mind that in actuality we would have coupling of the core modes and the cladding modes. The fact that a portion of the radiation field does not actually escape freely but finds itself trapped by reflection at the outer cladding boundary does not alter our conclusions very much. In most practical cases cladding modes will be suppressed by a lossy coating on the outside of the fiber, or they will scatter out of the cladding on account of the rough outer surface. In either case, power will not endure very long in cladding modes and may be considered as being lost, just as it would be had it radiated away freely. In those cases where these conditions are not met it is necessary to study the interaction of core and cladding modes in detail.

The derivation of the simplified guided modes of the fiber uses again the longitudinal E_z and H_z components from which the transverse components are derived by means of Eqs. (1.7-4)–(1.7-7). The longitudinal components must satisfy the reduced wave Eq. (1.7-9) which we now express in cylindrical coordinates:

$$\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + K_j^2\psi = 0 \tag{2.2-1}$$

with

$$K_j^2 = n_j^2k^2 - \beta^2 \tag{2.2-2}$$

and

$$k = \omega(\varepsilon_0\mu_0)^{1/2} = 2\pi/\lambda \tag{2.2-3}$$

Equation (2.2-1) is obtained from Maxwell's equations by eliminating the transverse field components and solving Maxwell's equations for either E_z or H_z. All field components have the common factor

$$\exp[i(\omega t - \beta z)] \tag{2.2-4}$$

which we omit from the equations for brevity.

To solve the reduced wave equation we substitute the trial solution

$$\psi = F(r)\cos\nu\phi \tag{2.2-5}$$

the infinite cross section. We obtain the same relation for all four types of modes:

$$A = \left[\frac{4(\mu_0/\varepsilon_0)^{1/2}\gamma^2 P}{e_\nu \pi a^2 n(n_1{}^2 - n_2{}^2)k^2 |J_{\nu-1}(\kappa a) J_{\nu+1}(\kappa a)|}\right]^{1/2} \tag{2.2-42}$$

with

$$e_\nu = \begin{cases} 2, & \text{for} \quad \nu = 0 \\ 1, & \text{for} \quad \nu \neq 0 \end{cases} \tag{2.2-42a}$$

A derivation of this formula is given at the end of this section.

The eigenvalue Eq. (2.2-39) must be solved by numerical techniques. However, near cutoff and far from cutoff of each mode, approximate closed-form solutions can be worked out. Near cutoff we have the inequality

$$\gamma a \ll 1 \tag{2.2-43}$$

We can thus use the approximations of the Hankel functions for small arguments. For $\nu = 0$, we use

$$H_0^{(1)}(i\gamma a) = (2i/\pi)\ln(\Gamma\gamma a/2) \tag{2.2-44}$$

with

$$\Gamma = 1.781672 \tag{2.2-45}$$

For $\nu \neq 0$, the following approximation holds:

$$H_\nu^{(1)}(i\gamma a) = -[i(\nu-1)!/\pi](2/i\gamma a)^\nu \tag{2.2-46}$$

Substitution of these relations into Eq. (2.2-38) yields, for $\nu = 0$,

$$\gamma a = (2/\Gamma)\exp[-(1/\kappa a)J_0(\kappa a)/J_1(\kappa a)] \tag{2.2-47}$$

At cutoff we have $\gamma a = 0$ and $\kappa_c d = V_c$. This last relation follows from

$$(\kappa^2 + \gamma^2)a^2 = V^2 = (n_1{}^2 - n_2{}^2)k^2 a^2 \tag{2.2-48}$$

We thus obtain the cutoff condition for $\nu = 0$ modes from Eq. (2.2-47):

$$J_1(V_c) = 0 \tag{2.2-49}$$

It is apparent from Eq. (2.2-48) that near cutoff we have, to a good approximation,

$$\kappa a \approx V_c + (V - V_c) - [(\gamma a)^2/2V_c] \tag{2.2-50}$$

so that we finally find the near cutoff approximation for $\nu = 0$ modes [neglecting the $(\gamma a)^2$ term in Eq. (2.2-50)]

$$\gamma a = \frac{2}{\Gamma}\exp\left[-\frac{1}{V}\frac{J_0(V)}{J_1(V)}\right] \tag{2.2-51}$$

For the modes with $\nu = 1$ we obtain from Eqs. (2.2-39), (2.2-44), and (2.2-46),

$$\kappa a J_0(\kappa a)/J_1(\kappa a) = (\gamma a)^2 \ln(\Gamma\gamma a/2) \tag{2.2-52}$$

The cutoff condition for $\nu = 1$ modes is thus

$$J_0(V_c) = 0 \tag{2.2-53}$$

We use Eqs. (2.2-50) and (2.2-53) and expand the function $J_0(\kappa a)$ with the help of the functional relation for the derivative of Bessel functions,

$$J_\nu'(\kappa a) = -(\nu/\kappa a)J_\nu(\kappa a) + J_{\nu-1}(\kappa a) = (\nu/\kappa a)J_\nu(\kappa a) - J_{\nu+1}(\kappa a) \tag{2.2-54}$$

(where the prime indicates the derivative with respect to the whole argument) obtaining

$$J_0(\kappa a) = -[(V - V_c) - (\gamma a)^2/2V_c]J_1(V_c) \tag{2.2-55}$$

If we now replace κa with V_c on the left-hand side of Eq. (2.2-52) and substitute Eq. (2.2-55), we obtain, for modes with $\nu = 1$,

$$(\gamma a)^2 = 2V_c(V - V_c)/[1 - 2\ln(\Gamma\gamma a/2)] \tag{2.2-56}$$

This is still an implicit equation for γa, but it can easily be solved with a few iterations. V_c is obtained as the solution of Eq. (2.2-53).

To find the approximation for $\nu \geqslant 2$ we expand $J_{\nu-1}(\kappa a)$ with the help of Eqs. (2.2-50) and (2.2-54) and the cutoff condition

$$J_{\nu-1}(V_c) = 0, \qquad \text{for} \quad \nu = 2, 3, \ldots \tag{2.2-57}$$

and obtain

$$J_{\nu-1}(\kappa a) = -[(V - V_c) - (\gamma a)^2/2V_c]J_\nu(V_c) \tag{2.2-58}$$

Equations (2.2-39) and (2.2-50) thus yield the near cutoff approximation for all modes with $\nu \geqslant 2$

$$\gamma a = \{2[(\nu-1)/\nu]V_c(V - V_c)\}^{1/2} \tag{2.2-59}$$

V_c is obtained as the solution of Eq. (2.2-57). The roots of the Bessel functions which solve Eqs. (2.2-49), (2.2-53), and (2.2-57) can be found in tables of Bessel functions [Je1, As1]. In Eq. (2.2-51) we did not expand the Bessel function $J_1(V)$ as we did in the other equations. The reason is twofold: The usual expansion of the type (2.2-55) or (2.2-58) would not work for the $V = 0$ solution of Eq. (2.2-49), since the expression $J_1(V_c)/V_c = 0/0$ is encountered in Eq. (2.2-54) for $V_c = 0$. It is, of course, easy to determine the limit of this undetermined ratio. The easiest approach would be to use the small argument approximation

$$J_\nu(V) = (1/\nu!)(V/2)^\nu \tag{2.2-60}$$